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An arrayed uniform eddy current probe design for crack monitoring and sizing of surface breaking cracks with the aid of a computational inversion technique

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ABSTRACT

This study demonstrates that eddy current testing can be an effective method for monitoring the growth of surface breaking cracks with the aid of computational inversion techniques. A uniform eddy current probe with 23 arrayed detectors was designed, and pseudo monitoring tests were carried out to measure signals due to six mechanical fatigue cracks introduced into type 316L austenitic stainless steel plates. In the test the position of the probe was fixed to simulate monitoring. The depths of the cracks were evaluated using a computational inversion method developed on the basis of k-nearest neighbor algorithm. The depths of the mechanical fatigue cracks whose actual depths were 1.1, 2.1, 3.1, 5.5, 6.7, and 8.5 mm were evaluated to be 0.9, 1.9, 3.8, 4.3, 7.0, and 5.7 mm, respectively. Additional simulations were conducted to demonstrate the stability of the method.

1. Introduction

Surface breaking cracks are one of the most harmful degradations considering their effect on structural integrity. It is therefore important to detect surface breaking cracks appearing in important structural components through periodical non-destructive inspections. Nevertheless, immediately replacing or repairing components with a surface breaking crack is not always reasonable, especially when taking such action requires large cost and long time for completion. This indicates that the vital role that non-destructive testing methods should play is not only to detect cracks but also to evaluate them. It is reasonable to leave a found crack as it is, if the evaluation on the basis of measured non-destructive testing signals assures that the crack remains sufficiently small and will not affect the integrity of structures until the next scheduled inspection. However, estimating the growth of a crack accurately is not always easy. In addition, several components are not so easily accessible, and thus conducting non-destructive inspection frequently is difficult.

One of the possible solutions for this problem is to monitor the growth of a crack by situating a probe where the crack is found and gather signals automatically and continuously. Among various non-destructive methods, those using ultrasonics are superior in evaluating the profile of cracks. However, in general they are not suitable for monitoring crack growth because of the need for couplant. In contrast, non-destructive methods using electromagnetic fields, especially eddy current testing, are regarded as promising candidates since they do not need physical contact. Whereas signals of eddy current testing do not contain information about the profile of a flaw so explicitly, recent studies have demonstrated that analyzing signals with the aid of numerical simulations enables to obtain quantitative information about the profile of a flaw [1–6]. However, it is likely that one cannot evaluate a flaw so quantitatively from eddy current signals measured in monitoring. This is because a probe is basically fixed during monitoring and thus the spatial resolution of signals gathered is quite sparse.

Based on the circumstances mentioned, this study aimed to evaluate the applicability of eddy current testing to the monitoring of the growth of surface breaking cracks. Actually, however, it is essentially difficult to size deep flaws quantitatively using eddy current testing. Furthermore, recent experiences have demonstrated that ultrasonic-based nondestructive testing methods can

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size flaws deeper than approximately 5 mm with a high accuracy, which implies that non-contact ultrasonic-based methods such as EMAT and laser-UT would be better candidates for monitoring the growth of deep cracks. For these reasons, this study evaluated the applicability from the viewpoints of (1) whether or not it is possible to size flaws whose depths are several millimeters in maximum, and (2) whether or not it is possible to assure that a flaw is deeper than a certain depth. A uniform eddy current probe with arrayed detectors was designed and experimental validations were carried out. This study used mechanical fatigue cracks introduced into type 316L austenitic stainless steel plates for the validations. In order to avoid discussions on mounting probe and to evaluate the feasibility of the monitoring itself, this study simulated monitoring by measuring signals due to the fatigue cracks with different depths without moving the probe. The surface lengths and the maximum depths of the fatigue cracks were evaluated with the aid of computational inversions, and were compared with the actual ones.

2. An array eddy current probe for crack monitoring

2.1. Design of an array eddy current probe

Since the position of a probe is fixed during monitoring, a probe for monitoring needs to have multiple detectors to gather signals at many points without being moved. Quite a few studies have proposed various structures of eddy current probes with multiple detectors [7–10]; this study designed an eddy current probe for crack monitoring on the basis of the structure of a uniform eddy current probe [10,11] because uniform eddy current probes are in general robust against various noises [12].

The picture of the probe designed in this study is presented in Fig. 1 with several important parameters. It consists of a large rectangular parallelepiped exciter and arrayed pancake type detectors attached to the bottom of the exciter. The direction of coil winding of the exciter is in the horizontal direction in the figure; the probe assumes that a flaw to be measured is oriented in parallel to the detector rows. The exciting frequency most suitable for the probe was set to 50 kHz that provides a depth of penetration of approximately 1.5 mm. This is because this study aims at the demonstration of quantitative sizing of cracks as deep as several millimeters and an earlier study [13] has reported that it would be possible to size a crack almost three times as deep as the depth of penetration if the crack can be regarded as nonconductive like a mechanical fatigue [14].

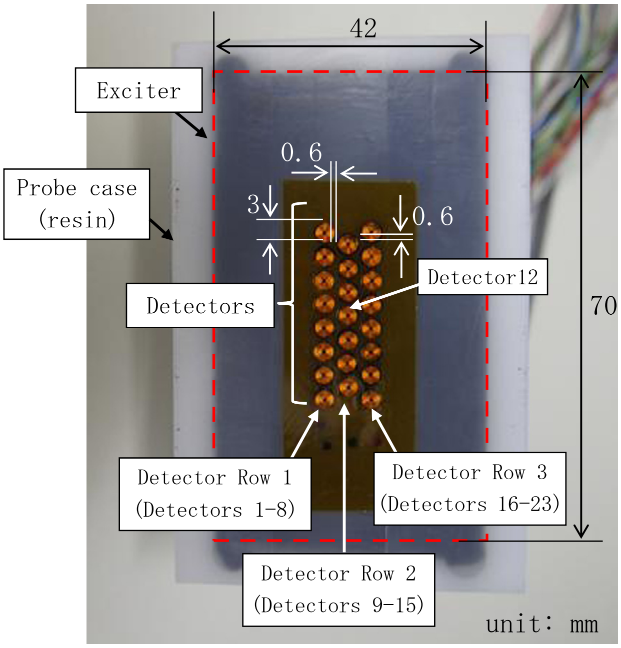

Fig. 1. Uniform eddy current probe with a detector array.

The exciter measures 70 mm in length, 42 mm in width, and 15 mm in height. The superior characteristics of the uniform eddy current probes basically stem from the fact that induced eddy currents flow almost uniformly below a probe. Whereas finite element simulations confirmed that it is preferable that an exciter is cubic from this point of view, a uniform eddy current probe having a cubic exciter is not suitable for the purpose of monitoring because this indicates that inducing eddy currents in a large area leads to a quite tall probe that would have problems with probe mounting. The numerical simulations also showed that induced eddy currents tend to concentrate near the edges of the exciter as the height of an exciter becomes shorter. Consequently, if the exciter is flat, eddy currents induced near the center of the exciter show relatively small change. Therefore, the length of the exciter was set to be approximately doubling the length of the area where the detectors are situated.

The detectors are 0.7 mm in height, 0.6 and 3 mm in inner and outer diameters, respectively. The number of detectors is 23 because of the specification of the eddy current instrument, aect-2000N-multi (Aswan ECT Co., Ltd., Osaka, Japan), used in this study. The detectors are situated in three rows and numbered as shown in the picture; Detector 12 is situated at the center of the probe.

2.2. Experimental verification to evaluate the characteristics of the probe

Preliminary experiments were carried out to evaluate the characteristics of the probe. The experiments measured signals due to a rectangular artificial slit machined into a type 316L stainless steel plate with a thickness of 25 mm. The width, depth and length of the slit are 0.5 mm, 20 mm and 40 mm, respectively. The trajectories of signals obtained when some of the detectors scanned directly above the slit are shown in Fig. 2. The probe was situated so that induced eddy currents flow perpendicular to the slit. The figure reveals that the trajectories of the signals from Detectors 9 and 15 are not so symmetric against the origin in contrast to that from Detector 12. This is because induced eddy currents do not flow uniformly below the detectors; the results indicate that analyzing signals quantitatively requires taking consideration of the characteristics of each detector individually.

3. Measuring fatigue cracks using the probe

This study prepared six type 316L stainless steel plate specimens; each of which contains a mechanical fatigue crack. The plate measured 20 mm in thickness, 300 mm in length, and 75 mm in width. Plates sufficiently thick compared with the depth of penetration were used so that the specimens can simulate general structures and results have generality. A starter notch with a length of approximately 12 mm, depth of 0.5 mm, and width of 0.6 mm was introduced at the center of the plates for localizing the emergence of a fatigue crack. The plates were served to cyclic four-point bending tests using a servohydraulic fatigue testing system (Instron 8802). The distances between the terminals of the four-point bending test were 50 and 200 mm; the minimum and maximum loads were 2.5 and 47.5 kN. The starter notches were removed before the measurements. Table 1 summarizes the surface lengths of the cracks, termed as Fc1-6, together with their